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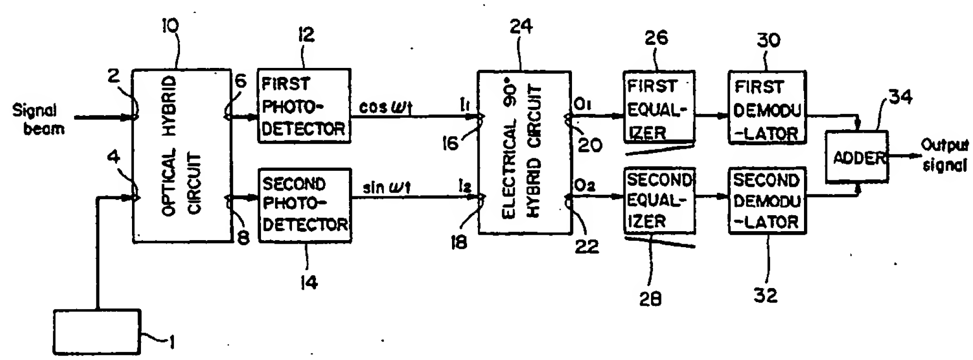
(54) Receiver for coherent optical communication.

(57) A receiver for coherent optical communication to be applied to a phase diversity system is disclosed. The receiver is capable of compensating the wavelength dispersion in an optical fiber to secure an enhanced receiving sensitivity.

FIG. I



RECEIVER FOR COHERENT OPTICAL COMMUNICATION

BACKGROUND OF THE INVENTION

The present invention relates to a receiver for coherent communication and, more specifically, to improvements in a phase diversity receiver for coherent optical communication.

The coherent optical communication system is suitable for long-distance signal transmission because its receiving sensitivity is higher than the current, practical intensity modulation direct detection system, and is suitable for bulk transmission owing to its capability of high-density multiplexing in transmitting signals using electromagnetic waves of frequencies in the frequency range of near visible light. The heterodyne system, the homodyne system and the phase diversity system are generally known as receiving systems for coherent optical communication. The phase diversity system, in particular, is suitable for high-speed transmission because the band width for the light wave detector (photoelectric converter) is half that for the photodetector of the heterodyne system. The phase diversity system, as compared with the homodyne system, is suitable for practical application because the phase diversity system does not require a light source with a very narrow spectral line width for emitting a carrier beam and a local-oscillator beam and does not need any phase locking circuit. However, whereas the heterodyne system is capable of compensating chromatic dispersion (group delay) in the optical fiber in the IF band (the intermediate frequency band), the homodyne system or the phase diversity system, which obtains signals directly in the baseband, is unable, in general, to compensate dispersion easily because the upper sideband and the lower sideband are folded. Accordingly, the phase diversity system needs improvements to enable the phase diversity system to compensate dispersion easily.

The heterodyne system mixes a received signal beam and a local-oscillator beam by the square-law function of the photodetector to produce an IF signal having a frequency, for example, a frequency in the microwave frequency range, corresponding to the difference between the frequency of the signal beam and that of the local-oscillator beam and demodulates the IF signal. In the heterodyne system, as well as in the foregoing other systems, the photodetector provides an IF signal having an amplitude proportional to the product of the amplitude of the received signal beam and that of the local-oscillator beam and, therefore, signals can be received at a a high sensitivity by using a local-oscillator beam of an appropriate intensity. However, in the heterodyne system, a band for the photodetector is in the range of 0.5B to 2.5B when the intermediate frequency f_{IF} is, for example, 1.5 times the bit rate B. Accordingly, when the bit rate is 10 Gb/s, the frequency band must be from 5 GHz to 25 GHz. Since it is difficult to provide a photodetector having a flat frequency response characteristic and a satisfactory noise characteristic in such a frequency band, the heterodyne system is not necessarily suitable for high-speed transmission. However, since the heterodyne system is able to achieve demodulation through envelope detection or the like, requirement of the light source relating to spectral line width is not very severe. Furthermore, in the heterodyne system, the upper sideband and lower sideband by modulation in an IF signal spectrum are not folded, the dispersion in an optical fiber can be compensated by using an equalizer employing a strip line.

In the homodyne system, the phase of the local-oscillator beam is controlled so that the carrier of the received signal beam and the local-oscillator beam are synchronized and a baseband signal is obtained directly without using an IF signal. Accordingly, similarly to condition with the intensity-modulated direct detection system, the bit rate B satisfies a desired band for the photodetector. Accordingly, the homodyne system is suitable for high-speed transmission. However, the homodyne system needs an optical phase synchronizing loop and a light source with a very small spectral line width. Moreover, since the upper sideband and lower sideband of the signal are folded on the baseband, the homodyne system is unable to compensate dispersion by an equalizer, which is different from the heterodyne system.

In the phase diversity system, in general, a local-oscillator beam of frequency slightly different from that of the carrier of the received signal beam is used, the received signal beam mixed with the branched local-oscillator beam having a predetermined phase shift, for example, 90°, for modulation. Since the band for the photodetector of the phase diversity system may be substantially equal to that for the homodyne system, the phase diversity system is able to construct a high-speed system. does not need the phase control of the local-oscillator beam, and hence does not need any light source capable of emitting light having a spectrum of very small spectral line width. However, the phase diversity system, similarly to the homodyne system, is unable to compensate chromatic dispersion in an optical fiber easily because the upper and lower sidebands are folded on the baseband.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a receiver for coherent optical communication, suitable for high-speed transmission, not requiring strict conditions for the spectral line width of light emitted by the light source and capable of compensating chromatic dispersion in an optical fiber. To put it briefly, it is an object of the present invention to enable a receiver for phase diversity system to compensate chromatic dispersion in an optical fiber.

In a first aspect of the present invention, a receiver for coherent optical communication comprises: an optical local oscillator for emitting a local-oscillator beam; an optical hybrid circuit 10 which is provided with a first optical input port for receiving a signal beam, a second optical input port for receiving the local-oscillator beam, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pair of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams respectively to the first optical output port and the second optical output port; a first photodetector for the photoelectric conversion of a beam received from first optical output port; a second photodetector for the photoelectric conversion of a beam received from the second optical output port; an electrical 90° hybrid circuit which is provided with an electrical input port for receiving the output signal of the first photodetector, a second electrical input port for receiving the output signal of the second photodetector, a first electrical output port and a second electrical output port, adds the signal received at the first electrical input port to the signal received at the second electrical input port after shifting the phase of the former by 90° to obtain an added signal and applies the added signal to the second electrical output port, adds the signal received at the second electrical input port to the signal received at the first electrical input port after shifting the phase of the former by 90° to obtain an added signal and applies the added signal to the first electrical output port; a first equalizer which delays a signal received from the first electrical output port by a delay corresponding to the frequency of the same received signal; a second equalizer which delays a signal received from the second electrical output port by a delay corresponding to the frequency of the same received signal; a first demodulator which demodulates the output signal of the first equalizer, a second demodulator which demodulates the output signal of the second equalizer; and an adder which adds the respective output signals of the first demodulator and the second demodulator.

Desirably, the proportional constant of either the first equalizer or the second equalizer, for determining the delay according to the frequency is positive and the sign of the proportional constant of the other, for determining the delay according to the frequency is negative.

In a second aspect of the present invention, a receiver for coherent optical communication comprises: an optical local oscillator for emitting a local-oscillator beam; an optical hybrid circuit which is provided with a first optical input port for receiving the signal beam, a second optical input port for receiving the local-oscillator beam, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams respectively to the first optical output port and the second optical output port; a first photodetector for the photoelectric conversion of a beam of the first optical output port; a second photodetector for the photoelectric conversion of a beam of the second optical output port; a first branching circuit for branching the output signal of the first photodetector; a second branching circuit for branching the output signal of the second photodetector 14; a first electrical 90° hybrid circuit which is provided with a first electrical input port 16 which receives one of the output branched signals of the first branching circuit, a second electrical input port which receives one of the output branched signals of the second branching circuit, a first electrical output port and a second electrical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90° to provide a added signal, applies the same added signal to the second electrical output port, adds the signal applied to the second electrical input port to the signal applied to the first electrical input port 16 after shifting the phase of the former by 90° to obtain an added signal and applies the same added signal to the first electrical output port; an inverter for inverting the polarity of the other output branched signal of either the first branching circuit or the second branching circuit; a second electrical 90° hybrid circuit which is provided with a first electrical input port for receiving the other output branched signal, not applied to the inverter for polarity inversion, a second electrical input port 18 for receiving the other branched signal inverted by the inverter, a first electrical output port and a second electrical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90° to provide an added signal, applies the same added

signal to the second electrical output port, adds the signal applied to the second electrical input port to the signal applied to the first electrical input port after shifting the phase of the former by 90° to provide an added signal and applies the same added signal to the first electrical output port; a first equalizer and a second equalizer which delay a signal received from the first electrical output port of the first electrical 90° hybrid circuit and a signal received from the second electrical output port of the second electrical 90° hybrid circuit by delays corresponding to their frequencies, respectively, or delay a signal received from the second electrical output port of the first electrical 90° hybrid circuit and a signal received from the first electrical output port of the second electrical 90° hybrid circuit by delays corresponding to their frequencies, respectively; a first demodulator for demodulating the output signal of the first equalizer; a second demodulator for demodulating the output signal of the second equalizer; and an adder for adding the output signals of the first demodulator and the second demodulator.

Desirably, the equalizers are the same in the sign of the ratio of change in delay to change in frequency. Accordingly, it is not necessary to use two kinds of equalizers differing from each other in characteristics.

In a third aspect of the present invention, a receiver for coherent optical communication comprises: a first optical branching circuit for branching a received signal beam; a local optical oscillator which emits a local-oscillator beam; a second optical branching circuit which branches the local-oscillator beam emitted by the local optical oscillator; a first optical hybrid circuit which is provided with a first optical input port which receives one of the branched beams of the signal beam branched by the first optical branching circuit, a second optical input port which receives one of the branched beams of the local-oscillator beam branched by the second optical branching circuit first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pair of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams to the first optical output port and the second optical output port, respectively; a second optical hybrid circuit which is provided with a first optical input port which receives the other branched beam of the signal beam branched by the first optical branching circuit, a second optical input port which receives the other branched beam of the local-oscillator beam branched by the second optical branching circuit, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the pair respectively, and applies the added beams to the first optical output port and the second optical output port, respectively; first to fourth photodetectors respectively for the photoelectric conversion of beams received from the first optical output port 6 and second output port of the first optical hybrid circuit and the first optical output port and second optical output port of the second optical hybrid circuit; a first electrical 90° hybrid circuit which is provided with a first electrical input port which receives the output signal of the first photodetector, a second electrical input port which receives the output signal of the second photodetector, a first electrical output port and a second electrical output port, adds the input signal applied to the first electrical input port to the input signal applied to the second electrical input port 18 after shifting the phase of the former by 90° to provide an added signal, applies the same added signal to the second electrical output port, adds the input signal applied to the second electrical input port to the input signal applied to the first input port after shifting the phase of the former by 90° to provide an added signal and applies the same added signal to the first electrical output port; a second electrical 90° hybrid circuit which is provided with a first electrical input port which receives the output signal of the third photodetector, a second electrical input port which receives the output signal of the fourth photodetector, a first electrical output port and a second electrical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90°, applies the added signal to the second electrical output port, adds the signal applied to the second electrical input port to the signal applied to the first electrical input port after shifting the phase of the former by 90° and applies the added signal to the first electrical output port; a first equalizer and a second equalizer which delay the output signals received from the first electrical output port of the first electrical 90° hybrid circuit and the second electrical output port of the second electrical 90° hybrid circuit by delays respectively corresponding to their frequencies, or delay the output signals received from the second electrical output port of the first electrical 90° hybrid circuit and the output signal of the first electrical output port of the second electrical 90° hybrid circuit by delays respectively corresponding to their frequencies; a first demodulator for demodulating the output signal of the first equalizer, a second demodulator for demodulating the output signal of the second equalizer and an adder for adding the output signals of the first demodulator and the second demodulator.

Desirably, the first equalizer and the second equalizer are the same in the sign of the ratio of change in delay to change in frequency.

In any one of the receivers in the first, the second and the third aspect of the present invention, the electrical 90° hybrid circuit provides separately a signal based on the upper sideband and a signal based on the lower sideband folded on the baseband, so that the compensation of wavelength dispersion in an optical fiber can be achieved.

A receiver for coherent optical communication in a fourth aspect of the present invention comprises: a local oscillator which emits a local-oscillator beam; an optical hybrid circuit which is provided with a first optical input port for receiving the received signal beam, a second optical input port for receiving the local-oscillator beam, a first optical output port and a second optical output port, branches the received signal beam and the local-oscillator beam, adds one pair of the branched signal beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair, respectively, and applies the added beams respectively to the first and second optical output ports; a first photodetector for the photoelectric conversion of a beam of the first optical output port; a second photodetector for the photoelectric conversion of the output signal of the second optical output port; an oscillator which generates a signal of a fixed frequency; a first mixer which adds the signal generated by the oscillator with the output signal of the first photodetector; a second mixer which adds the signal generated by the oscillator with the output signal of the second photodetector; an electrical 90° hybrid circuit which is provided with a first electrical input port for receiving the output signal of the first mixer, a second electrical input port for receiving the output signal of the second mixer, a first electrical output port and a second electrical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90°, applies the added signal to the second electrical output port, adds the input signal applied to the second electrical input port to the input signal applied to the first electrical input port after shifting the phase of the former by 90° and applies the added signal to the first electrical output port; and an equalizer which delays the output signal of the first or second electrical output port by a delay corresponding to its frequency,

This receiver up-converts a baseband signal again to a signal in the IF band. Thus, the receiver, similarly to the heterodyne receiver, executes demodulation again after compensating dispersion in an optical fiber to obtain a signal in the baseband.

The above and other objects, features and advantages of the present invention and the manner of realizing them will become more apparent, and the invention itself will be understood, from a study of the following description and appended claims, with reference had to the attached drawings showing receivers in preferred embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a receiver in a first embodiment according to the present invention;
Figure 2 is a block diagram of a receiver in a second embodiment according to the present invention;
Figure 3 is a block diagram of a receiver in a third embodiment according to the present invention;
Figures 4A, 4B and 4C are circuit diagrams of optical hybrid circuits;
Figure 5 is a graph showing a mode of polarization of a signal beam and a local-oscillator beam applied to the optical hybrid circuit of Fig. 4A or 4B;
Figures 6A and 6B are graphs showing modes of polarization of a signal beam and a local-oscillator beam applied to the optical hybrid circuit of Fig 4A or 4B;
Figures 7A and 7b are graphs showing further modes of polarization of a signal beam and a local-oscillator beam applied to the optical hybrid circuit of Fig. 4A or 4B;
Figure 8 is a graph of assistance in explaining the circular polarization and elliptic polarization of linearly polarized light, showing an index ellipsoid;
Figures 9A and 9B are circuit diagrams of double-balanced photodetectors;
Figures 10A, 10B and 10C are circuit diagrams of optical hybrid circuits suitable for a double-balanced photodetector;
Figures 11A and 11B are graphs of assistance in explaining the relative relation between a signal beam and a local-oscillator beam on the frequency axis;
Figures 12A and 12B are graphs of assistance in explaining a state where the upper and lower sidebands are folded, and delay attributable to wavelength dispersion;
Figures 13A and 13B are graphs of assistance in explaining the delaying characteristics of an equalizer necessary for the compensation of delay in a signal in the upper sideband and a signal in the lower sideband attributable to the wavelength dispersion; and

Figure 14 is a block diagram of a receiver in a fourth embodiment according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As shown in Fig. 1, in a first embodiment of the present invention, a receiver for coherent optical communication comprises: an optical local oscillator 1 for emitting a local-oscillator beam; an optical hybrid circuit 10 which is provided with a first optical input port 2 for receiving a signal beam, a second optical input port 4 for receiving the local-oscillator beam, a first optical output port 6 and a second optical output port 8, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams respectively to the first optical output port 6 and the second optical output port 8; a first photodetector 12 for the photoelectric conversion sof a beam received from first optical output port 6; a second photodetector 14 for the photoelectric conversion of a beam received from the second optical output port 8; an electrical 90° hybrid circuit 24 which is provided with an electrical input port 16 for receiving the output signal of the first photodetector 12, a second photodetector 14, a first electrical output port 20 and a second electrical output port 22, adds the signal received at the first electrical input port 16 to the signal received at the second electrical input port 18 after shifting the phase of the former by 90° to obtain an added signal and applies the added signal to the second electrical output port 22, adds the signal received at the second electrical input port 18 to the signal received at the first electrical input port 16 after shifting the phase of the former by 90° to obtain an added signal and applies the added signal to the first electrical output port 20; a first equalizer 26 which delays a signal received from the first electrical output port 20 by a delay corresponding to the frequency of the same received signal; a second equalizer 28 which delays a signal received fro the second electrical output port 22 by a delay corresponding to the frequency of the same received signal; a first demodulator 30 which demodulates the output signal of the first equalizer 26, a second demodulator 32 which demodulates the output signal of the second equalizer 28; and an adder 34 which adds the respective output signals of the first demodulator 30 and the second demodulator 32.

The proportional constant of either the first equalizer 26 or the second equalizer 28, for determining the delay according to the frequency is positive and the sign of the proportional constant or the other, for determining the delay according to the frequency is negative.

As shown in Fig. 2, in a second embodiment of the present invention, a receiver for coherent optical communication comprises: an optical local oscillator 1 for emitting a local-oscillator beam; an optical hybrid circuit 10 which is provided with a first optical input port 2 for receiving the signal beam, a second optical input port 4 for receiving the local-oscillator beam, a first optical output port 6 and a second optical output port 8, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams respectively to the first optical output port 6 and the second optical output port 8; a first photodetector 12 for the photoelectric conversion of a beam of the first optical output port 6; a second photodetector 14 for the photoelectric conversion of a beam of the second optical output port 8; a first branching circuit 36 for branching the output signal of the first photodetector 12; a second branching circuit 38 for branching the output signal of the second photodetector 14; a first electrical 90° hybrid circuit 24A which is provided with a first electrical input port 16 which receives one of the output branched signals of the first branching circuit 36, a second electrical input port 18 which receives one of the output branched signals of the second branching circuit 38, a first electrical output port 20 and a second electrical output port 22, adds the signal applied to the first electrical input port 16 to the signal applied to the second electrical input port 18 after shifting the phase of the former by 90° to provide an added signal, applies the same added signal to the second electrical output port 22, adds the signal applied to the second electrical input port 18 to the signal applied to the first electrical input port 16 after shifting the phase of the former by 90° to obtain an added signal and applies the same added signal to the first electrical output port 20; an inverter 40 for inverting the polarity of the other output branched signal of either the first branching circuit 36 or the second branching circuit 38; a second electrical 90° hybrid circuit 24B which is provided with a first electrical input port 16 for receiving the other output branched signal, not applied to the inverter 40 for polarity inversion, a second electrical input port 18 for receiving the other branched signal inverted by the inverter 40, a first electrical output port 20 and a second electrical output port 22, adds the signal applied to the first electrical input port 16 to the signal applied to the second electrical input port 18 after shifting the phase of the former by 90° to provide an added signal, applies the same added signal to the second electrical output port 22, adds the signal applied to the second electrical input port 18 to the

signal applied to the first electrical input port 16 after shifting the phase of the former by 90° to provide an added signal and applies the same added signal to the first electrical output port 20; a first equalizer 26 and a second equalizer 28′ which delay a signal received from the first electrical output port 20 of the first electrical 90° hybrid circuit 24a and a signal received from the second electrical output port 22 of the second electrical 90° hybrid circuit 24B by delays corresponding to their frequencies, respectively, or delay a signal received from the second electrical output port 22 of the first electrical 90° hybrid circuit 24a and a signal received from the first electrical output port 20 of the second electrical 90° hybrid circuit 24B by delays corresponding to their frequencies, respectively; a first demodulator 30 for demodulating the output signal of the first equalizer 26; a second demodulator 32 for demodulating the output signal of the second equalizer 28′; and an adder 34 for adding the output signals of the first demodulator 30 and the second demodulator 32.

The equalizers 26 and 28′ are the same in the sign of the ratio of change in delay to change in frequency. Accordingly, it is not necessary to use two kinds of equalizers differing from each other in characteristics.

As shown in Fig. 3, in a third embodiment of the present invention, a receiver for coherent optical communication comprises: a first optical branching circuit 42 for branching a received signal beam; a local optical oscillator 1 which emits a local-oscillator beam; a second optical branching circuit 44 which branches the local-oscillator beam emitted by the local optical oscillator 1; a first optical hybrid circuit 10A which is provided with a first optical input port 2 which receives one of the branched beams of the signal beam branched by the first optical branching circuit 42, a second optical input port 4 which receives one of the branched beams of the local-oscillator beam branched by the second optical branching circuit 44, a first optical output port 6 and a second optical output port 8, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams to the first optical output port 6 and the second optical output port 8, respectively; a second optical hybrid circuit 10B which is provided with a first optical input port 2 which receives the other branched beam of the signal beam branched by the first optical branching circuit 42, a second optical input port 4 which receives the other branched beam of the local-oscillator beam branched by the second optical branching circuit 44, a first optical output port 6 and a second optical output port 8, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the pair respectively, and applies the added beams to the first optical output port 6 and the second optical output port 8, respectively; first to fourth photodetectors 12, 14, 12′ and 14′ respectively for the photoelectric conversion of beams received from the first optical output port 6 and second output port 8 of the first optical hybrid circuit 10A and the first optical output port 6 and second optical output port 8 of the second optical hybrid circuit 10B; a first electrical 90° hybrid circuit 24a which is provided with a first electrical input port 16 which receives the output signal of the first photodetector 12, a second electrical input port 18 which receives the output signal of the second photodetector 14, a first electrical output port 20 and a second electrical output port 22, adds the input signal applied to the first electrical input port 18 after shifting the phase of the former by 90° to provide an added signal, applies the same added signal to the second electrical output port 22, adds the input signal applied to the second electrical input port 18 to the input signal applied to the first input port 16 after shifting the phase of the former by 90° to provide an added signal and applies the same added signal to the first electrical output port 20; a second electrical 90° hybrid circuit 24b which is provided with a first electrical input port 16 which receives the output signal of the third photodetector 12′, a second electrical input port 18 which receives the output signal of the fourth photodetector 14′, a first electrical output port 20 and a second electrical output port 22, adds the signal applied to the first electrical input port 16 to the signal applied to the second electrical input port 18 after shifting the phase of the former by 90°, applies the added signal to the second electrical output port 22, adds the signal applied to the second electrical input port 18 to the signal applied to the first electrical input port 16 after shifting the phase of the former by 90° and applies the added signal to the first electrical output port 20; a first equalizer 26 and a second equalizer 28′ which delay the output signals received from the first electrical output port 20 of the first electrical 90° hybrid circuit 24A and the second electrical output port 22 of the second electrical 90° hybrid circuit 24B by delays respectively corresponding to their frequencies, or delay the output signals received from the second electrical output port 22 of the first electrical 90° hybrid circuit 24a and the output signal of the first electrical output port 20 of the second electrical 90° hybrid circuit 24b by delays respectively corresponding to their frequencies; a first demodulator 30 for demodulating the output signal of the first equalizer 26, a second demodulator 32 for demodulating the output signal of the second equalizer 28′; and an adder for adding the output signals of the first demodulator 30 and the second demodulator 32.

The first equalizer 26 and the second equalizer 28′ are the same in the sign of the ratio of change in delay to change in frequency.

In any one of the receivers in the first, the second and the third embodiments of the present invention, the electrical 90° hybrid circuit provides separately a signal based on the upper sideband and a signal based on the lower sideband folded on the baseband, so that the compensation of wavelength dispersion in an optical fiber can be achieved.

Prior to the detailed description of receivers operation in preferred embodiments according to the present invention, the circuit configurations of optical hybrid circuits will be described with reference to Figs. 4A, 4B and 4C.

An optical hybrid circuit shown in Fig. 4A comprises an optical coupler 48 which adds the signal beam applied to the first optical input port 2 to the local-oscillator beam applied to the second optical input port 4 to provide a added beam and branches the added beam to provide branched beams, and a polarizing splitter 50 which splits at least one of the branched beams branched by the optical coupler 48 so that the polarized components of the local-oscillator beam and the signal beam are applied to the first optical output port 6 and the second optical output port 8.

An optical hybrid circuit shown in Fig. 4B comprises a first polarizing splitter 52 and a second polarizing splitter 54 which splits the signal beam received at the first optical input port 2 and the local-oscillator beam received at the second optical input port 4 so that the polarized components of the signal beam and the local-oscillator beam are provided, and two optical couplers 56 and 58 which mix beams having the same plane of polarization provided by the two polarizing splitters 52 and 54 and apply the added beams to the first output port 6 and the second output port 8.

An optical hybrid circuit shown in Fig. 4C comprises two optical couplers 60 and 62 which branch the signal beam received at the first optical input port 2 and the second optical input port 4, an optical coupler 64 which adds the signal beam (or the local-oscillator beam) branched by the optical coupler 60 to the local-oscillator beam (or the signal beam) branched by the optical coupler 62 and applies the added beam to the first optical output port 6, a phase shifter 66 which shifts the phase of the signal beam (or the local-oscillator beam) branched by the optical coupler 60 by 90°, and an optical coupler 68 which adds the signal beam (or the local-oscillator beam) branched by the optical coupler 60 and phase-shifted by the phase shifter 66 to the local-oscillator beam (or the signal beam)branched by the optical coupler 62 and applies the added beam to a second optical output port 8.

For the optical hybrid circuit shown in Fig. 4A or 4B, the signal beam or the local-oscillator beam is applied to the first optical input port 2 in a linearly polarized beam and the other is applied to the second optical input port 4in a circularly polarized beam, or the signal beam and the local-oscillator beam are applied respectively to the first optical input port 2 and the second optical input port 4 in elliptically polarized beams having a phase shift equal to the phase difference between the linear-polarized beam and the circular-polarized beam. For the optical hybrid circuit shown in Fig. 4C, the signal beam and the local-oscillator beam are applied in linearly polarized beams respectively to the first optical input port 2 and the second optical input port 4. The optical path length is adjusted and the plane of polarization is secured so that the polarized state is maintained as far as the light receiving surface.

The signal beam and the local-oscillator beam are applied to the optical hybrid circuit in such specific states of polarization to realize a phase diversity system by branching the received signal beam into two branch beams, adding the 90°-shifted local-oscillator beam to the branched signal beams and making the added beams reach the light receiving surfaces.

Each optical coupler may be of a fiber fusion type utilizing evanescent wave coupling or of a waveguide type, desirably, an optical coupler capable of conserving the plane of polarization. The optical couplers may be half mirrors.

Fig. 5 shows a graph of assistance in explaining a desirable state of polarization of the signal beam and the local-oscillator beam applied to the optical hybrid circuit shown in Fig. 4A or 4B included in the receiver shown in Fig. 1 or 2, in which the direction of light propagation coincides with that of the z-axis, the plane of polarization of a P-polarized beam divided by the polarizing splitter is included in the x-z plane and the plane of polarization of an S-polarized beam is included in the y-z plane of an orthogonal three-dimensional coordinate system, which applies also to Figs. 6 and 7. The state of polarization of the signal beam and that of the local-oscillator beam may be interchanged. In the following description, it is assumed that the signal beam is a linearly polarized beam and the local-oscillator beam is a circularly polarized beam. In Fig. 5, as circle of 70 is the projection of the locus of the tip of the field vector of the local-oscillator beam propagating in a circularly polarized beam on the x-y plane, and a line segment 72 is the projection of the locus of the extremity of the field vector of the signal beam propagating in a linearly polarized beam on the x-y plane. The local-oscillator beam 70 may be either a clockwise circularly polarized beam or a counterclockwise

circularly polarized beam with respect to the direction of propagation. When the signal beam 72 is a 45° linearly polarized beam having a plane of polarization inclined at an angle of 45° to the positive direction of the x-axis in a counterclockwise direction, the branched signal beams divided by the polarizing splitter are equal to each other in power and hence optical powers that appear respectively at the first optical output port 6 and the second optical output port 8 are equal to each other to enhance the receiving sensitivity. Hereinafter, a linearly polarized beam having a plane of polarization inclined at an angle of θ° to the positive direction of the x-axis in a counterclockwise direction will be designated as a θ° linearly polarized beam.

When the local-oscillator beam 70 and the signal beam 72 of such characteristics are applied respectively, for example, to the first optical input port 2 and second optical input port 4 of the optical hybrid circuit shown in Fig. 4A, the optical coupler 48 adds the local-oscillator beam 70 and the signal beam 72, and the polarizing splitter 50 splits the same. The phase shift between the split signal beams is zero, but the phase shift between the split local-oscillator beams is at the polarizing splitter 50. The 90°-shifted local-oscillator beams are added to the branched signal beams and the added beams are applied to the first optical output port 6 and the second optical output port 8.

When the signal beam 72 and the local-oscillator beam 70 are applied respectively to the first optical input port 2 and second optical input port 4 of the optical hybrid circuit shown in Fig. 4B, the optical hybrid circuit adds the 90°-shifted local-oscillator beams to the branched signal beams and applies the added beams respectively to the first optical output port 6 and the second optical output port 8 after performing light beam adding and light beam branching in order reverse to that in which the optical hybrid circuit shown in Fig. 4A performs the same.

Figs. 6A and 6B are graphs of assistance in explaining desirable states of polarization of a signal beam and a local-oscillator beam applied to the optical hybrid circuit shown in Figs. 4A and/or 4B included in a receiver shown in Fig. 3. When a signal beam and a local-oscillator beam applied to either the first optical hybrid circuit 10A or the second optical hybrid circuit 10B are a 45° linearly polarized beam and a clockwise circularly polarized beam, as shown in Fig. 6A, respectively, a 135° linearly polarized beam and a clockwise circularly polarized beam as shown in Fig. 6B are applied as a signal beam and a local-oscillator beam, respectively, to the other optical hybrid circuit. Thus, the two optical hybrid circuits shift the phase of the local-oscillator beam in reverse directions, respectively. For example, when the phase of the local-oscillator beam added to the signal beam to be applied to the first optical port 6 of one of the two optical hybrid circuits is advanced by 90° relative to the phase of the local-oscillator beam added to the signal beam to be applied to the second optical output port 8 of the same optical hybrid circuit, the phase of the local-oscillator beam added to the signal beam to be applied to the first optical output port 6 of the other optical hybrid circuit can be delayed by 90° relative to the local-oscillator beam added with the signal beam to be applied to the second optical output port 8 of the same optical hybrid circuit.

When a signal beam and a local-oscillator beam applied to one of the two optical hybrid circuits are a 45° linearly polarized beam and a clockwise circularly polarized beam as shown in Fig. 7A, respectively, the respective phase shifting directions of the two optical hybrid circuits in shifting the phases of the local-oscillator beams applied respectively to the two optical hybrid circuits can be reverse to each other when a signal beam and a local-oscillator beam applied to the other optical hybrid circuit are a 45° linearly polarized beam and a counterclockwise circularly polarized beam as shown in Fig. 7B, respectively.

When the receiver in the first or second embodiment of the present invention employs the optical hybrid circuit shown in Fig. 4C, the interference efficiency can be increased to a maximum by using linearly polarized beams having planes of polarization coinciding with each other as the input signal beam and the input local-oscillator beam and by maintaining the coincidence of the planes of polarization as far as the light receiving surfaces to increase the receiving sensitivity to a maximum.

When the receiver in the third embodiment of the invention employs the optical hybrid shown in Fig. 4C, the phase shift produced by one of the phase shifters 66 is +90° when the phase shift produced by the other is -90° (+270°).

Although the description made with reference to Figs. 5 to 7B is based on an assumption that the signal beam and the local-oscillator beam applied to the optical hybrid circuit shown in Fig. 4A or 4B are a linearly polarized beam and a circularly polarized beam, respectively, the signal beam and the local-oscillator beam applied respectively to the first optical input port 2 and the second optical input port 4 may be elliptically polarized beams, which will be described hereinafter with reference to Fig. 8.

Fig. 8 shows an index ellipsoid of assistance in explaining circular polarization and elliptic polarization. Generally, when a local-oscillator beam is emitted by a local light source, such as a laser diode, in a linearly polarized beam like the signal beam 72 shown in Fig. 5, the linearly polarized local-oscillator beam can be converted into a circularly polarized beam by using a quarter wavelength plate which functions at different

refractive indices respectively with a polarized component having a plane of polarization included in the x-z plane and a polarized component having a plane of polarization included in the y-z plane. The quarter wavelength plate is a birefringent plate having a given thickness and disposed in a given crystal orientation. Suppose that the refractive index of the birefringent plate with an ordinary beam is n_o, a maximum refractive index of the same with an extraordinary beam is n_e ($n_o < n_e$), a light beam is traveling in the direction of an arrow S from the origin O of an orthogonal three-dimensional coordinate system having the z-axis coinciding with the optical axis of the birefringent plate, and the projection of the arrow S on the X-Y plane is included in the Y-axis. Then, the index ellipsoid is expressed by

$(X^2/n_o^2) + (Y^2/n_o^2) + (Z^2/n_e^2) = 1 \quad (1)$

The refractive index n_o with the ordinary beam is a constant corresponding to the distance OP between the origin O and a point P where a circle A obtained by intersecting the index ellipsoid with the X-Y plane intersects an ellipse B obtained by intersecting the index ellipsoid with a plane including the origin O and perpendicular to the direction S of propagation. The refractive index n_e' with the extraordinary beam varies according to the angle θ between the direction S of propagation and the Z-axis and corresponds to the distance OQ between the origin O and a point Q where the ellipse B intersects the Y-Z plane. The refractive index n_e' with the extraordinary beam varies continuously between n_o and n_e according to the direction S of propagation. Since the difference between the refractive index of the birefringent plate with the ordinary beam and that of the same with the extraordinary beam varies according to the direction S of propagation of the extraordinary beam, the input local-oscillator beam, i.e., the linearly polarized beam can be converted into a circularly polarized beam by disposing orienting the optical axis of the birefringent plate so that the direction S of propagation of the local-oscillator beam coincides with the Y-axis ($\theta = 90^\circ$) so that the plane of polarization of the local-oscillator beam inclined at an angle of 45° to the lines OP and OQ and by selectively determining the thickness of the birefringent plate so that the phase difference between the orthogonal polarized components of the local-oscillator beam is 90°.

Accordingly, it is possible to use an elliptically polarized beam having an appropriate ellipticity as either the signal beam or the local-oscillator beam, and an elliptically polarized beam having a corresponding ellipticity as the other beam, and to make the phase relation between the elliptically polarized beams correspond to the phase relation between a linearly polarized beam and a circularly polarized beam by utilizing the characteristics of the birefringent plate.

Two dual-detector balanced optical receivers (DBORs) of different circuit configurations will be described hereinafter with reference to Figs. 9A and 9B.

The DBOR shown in Fig. 9A amplifies voltage changes corresponding to photocurrent changes in two light receiving elements 74 and 76, such as pin photodiodes, having the same characteristics respectively by amplifiers 78 and 80, and applies the amplified voltage changes to subtracter 82 for subtraction. When the respective optical path lengths of light beams incident on the light receiving elements 74 and 76 are adjusted, the respective phases of signal components falling on the light receiving elements 74 and 76 are opposite to each other and the respective phases of intensity noise components are the same due to the inversion of optical phase by the optical coupler. Accordingly, the signal components are added and the intensity noise components cancel each other to suppress the intensity noise of the local oscillator or the like. It is also possible to connect light receiving elements 84 and 86 having the same characteristics in series as shown in Fig. 9B, and the potential variation at the connecting point may be amplified by an amplifier 88.

When the DBOR is employed, the output signal beams and the output local oscillator beams of the optical hybrid circuit must be applied through two paths to the two light receiving elements, and hence the configurations of the optical hybrid circuits shown in figs. 4A, 4B and 4C must be modified. Figs. 10A, 10B and 10C are modifications of the optical hybrid circuits shown in Figs. 4A, 4B and 4C, respectively.

An optical hybrid circuit shown in Fig. 10A is provided, in addition to the polarizing splitter 50 for splitting one of the beams branched by the optical coupler 48, a polarizing splitter 90 for splitting the other beam. P waves split by the polarizing splitters 50 and 90 are applied respectively to the optical output ports 6a and 6b of the first optical output 6. S waves split by the polarizing splitters 50 and 90 are applied to the optical output ports 8a and 8b of the second optical output port 8. The two P waves and the two S waves are applied through optical paths having appropriate optical path lengths respectively to the two light receiving elements 74 and 76, or 84 and 86 of the DBOR.

An optical hybrid circuit shown in Fig. 10B branches each of added beams added by the optical couplers 56 and 58 into two branch beams. The optical outputs of the optical coupler 56 is applied to the optical output ports 6a and 6b of the first optical output port 6, and the optical outputs of the optical coupler 58 are applied to the optical output ports 8a and 8b of the second optical output port 8.

An optical hybrid circuit shown in Fig. 10C, similarly to that shown in Fig. 10B, applies the respective

two optical outputs of two optical couplers 64 and 68 respectively to the first optical output port 6 and the second optical output port 86.

The concrete circuit configuration and functions of the electrical 90° hybrid circuit 24 employed in the receiver embodying the present invention will be described hereinafter.

The electrical 90° hybrid circuit 24 transmits a signal from the first electrical input port 16 to the first electrical output port 20 and from the second electrical input port 18 to the second electrical output port 22 at 3 dB loss without changing the phase of the signal, and transmits a signal from the first electrical input port 16 to the second electrical output port 22 and from the second electrical input port 18 to the first electrical output port at 3 dB loss changing the phase of the signal by 90°. The circuit configuration is changed according to the frequency band of the signal.

Delays given to signals by the equalizers 26 and 28 are dependent on the frequencies of the signals. The equalizers 26 and 28 may comprise, for example, a microstrip line or a slot line having a linear characteristic in a wide band.

When the demodulator 30 and 32 are of a DPSK (differential phase shift keying) system, the circuit configurations of the demodulators 30 and 32 are determined on the basis of the principle of demodulation of 1-bit delay.

The characteristic operation of the receivers in the first to third embodiments according to the present invention will be described hereinafter.

Assuming that the receiver in the first embodiment operates in a PSK mode,

$E_S = C_1 \cos(\omega_S t + \phi)$ (2)

where E_S is the field intensity of the input signal beam, C_1 is an optional constant, ω_S is the angular frequency of the carrier, ϕ is the phase difference between the electric field of the signal beam and that of the local-oscillator beam, which remains constant in one time slot (the reciprocal of bit rate). The signal beam is divided by the optical hybrid circuit 10 into two branch signal beams, the two branch signal beams are added to the local-oscillator beams of angular frequency having 90° phase difference, and the added beams are subjected to the square-law detection of the photodetectors 12 and 14. The photodetectors 12 and 14 produce photocurrents I_1 and I_2 expressed by

$I_1 = C_2 \cos(\omega_{OFF} t + \phi)$ (3)

$I_2 = -C_2\, \mathrm{sgn}(\omega_S - \omega_L) \cdot \sin(\omega_{OFF} t \_ \phi)$ (4)

where C_2 is an optional constant, ω_{OFF} is offset angular frequency for the AFC (automatic frequency control) of the local-oscillator beam expressed by

$\omega_{OFF} = |\omega_S i- \omega_L|$ (5)

The $\mathrm{sgn}(\omega_S - \omega_L)$ is defined by

$\mathrm{sgn}(\omega_S - \omega_L) = 1\ (\omega_S - \omega_L > 0) = -1\ (\omega_S - \omega_L < 0)$ (6)

To facilitate qualitative understanding, expressions (3) and (4) are changed as follows taking into consideration only the relative relation between these phases.

$I_1 = \mathrm{cost}\ \omega t$ (7)

$I_2 = \mathrm{sgn}(\omega_S - \omega_L) \cdot \sin \omega t$ (8)

Similarly, input signals I_3 and I_4 to the additional electrical 90° hybrid circuit 24B included in the receiver in the second or third embodiment are

$I_3 = \cos \omega t$ (9)

$I_4 = \mathrm{sgn}(\omega_S - \omega_L) \cdot \sin \omega t$ (8)

Representing an operation for delaying the phase by 90° by "*",

$(\cos \omega t)^* = \sin \omega t$ (11)

$(\sin \omega t)^* = -\cos \omega t$ (12)

Output signals O_1, O_2, O_3 and O_4 corresponding to the inputs to the electrical 90° hybrid circuit 24 are

$O_1 = 1/\sqrt{2} \cdot (I_1 + I_2^*) = 1/\sqrt{2} \cdot (1 + \mathrm{sgn}(\omega_S - \omega_L)) \cdot \cos \omega t$ (13)

$O_2 = 1/\sqrt{2} \cdot (I_1^* + I_2) = 1/\sqrt{2} \cdot (1 - \mathrm{sgn}(\omega_S - \omega_L)) \cdot \sin \omega t$ (14)

$O_3 = 1/\sqrt{2} \cdot (I_3 + I_4^*) = 1/\sqrt{2} \cdot (1 - \mathrm{sgn}(\omega_S - \omega_L)) \cdot \cos \omega t$ (15)

$O_4 = 1/\sqrt{2} \cdot (I_3^* + I_4) = 1/\sqrt{2} \cdot (1 + \mathrm{sgn}(\omega_S - \omega_L)) \cdot \sin \omega t$ (16)

The following table shows the contents of expressions (13) to (16).

As shown in the table, the electrical 90° hybrid circuit provides output signals in the upper sideband and those in the lower sideband separately, and hence signal degradation attributable to wavelength dispersion can be prevented by delaying the output signals according to their frequencies by the equalizers, which will be described below with reference to Figs. 11 to 13.

Table

Output signal	O_1	O_2	O_3	O_4
$0 < \omega_S - \omega_L$ (upper sideband)	$\sqrt{2} \cdot \cos \omega t$	0	0	$\sqrt{2} \cdot \sin \omega t$
$0 > \omega_S - \omega_L$ (lower sideband)	0	$\sqrt{2} \cdot \sin \omega t$	$\sqrt{2} \cdot \cos \omega t$	0

In the phase diversity system, the relation between the frequency f_S of the signal beam and the frequency f_L of the local-oscillator bed is $f_L < f_S$ (Fig. 11A) or $f_S < f_L$ (Fig. 11B). In either case, the upper sideband (continuous line) and lower sideband (broken line) of the output signals of the photodetectors 12 and 14 are folded as shown in Figs. 12A and 12B. Figs. 12A and 12B correspond respectively to Figs. 11A and 11B. Generally, when the optical transmission line is a quartz optical fiber of zero dispersion in the 1.3 µm band, the wavelength dispersion causes smaller delays for higher frequencies in upper sideband signals, and causes greater delays for higher frequencies in lower sideband signals. Accordingly, the equalizer is unable to compensate the output signal of the photodetector directly, which is a previously describe problem in the general phase diversity system.

In the receivers in the first to third embodiments of the present invention, the electrical 90° hybrid circuit 24 is able to provide the upper sideband signal and the lower sideband signal separately. Therefore, the wavelength dispersion can be compensated by using an equalizer which gives greater delays for higher frequencies for the upper sideband signal, and an equalizer which gives smaller delays for higher signal frequencies for the lower sideband signal.

In the receiver in the first embodiment of the present invention, the output signals O_1 and O_2 of the electrical 90° hybrid circuit 24 are an upper sideband signal and a lower sideband signal as shown in the table. Therefore, the respective characteristics of the equalizers 26 and 28 are reverse to each other. On the other hand, in the receivers in the second and third embodiments of the present invention, only the upper sideband signals O_1 and O_4 among the output signals of the first electrical 90° hybrid circuit 24A and the second electrical 90° hybrid circuit 24B are used, and hence the equalizers 26 and 28 are the same in characteristics. When the outputs O_2 and O_3 are used, equalizers having the same characteristics which are reverse to those of the equalizers employed when the outputs O_1 and O_4 are used may be employed.

In the receivers in the first to third embodiments of the present invention, the upper sideband signal and the lower sideband signal are separated from each other on a principle similar to an image rejection principle. Therefore, dispersion in each signal must be compensated by an equalizer to realize phase diversity. Accordingly, at least two equalizers are necessary. A receiver in a fourth embodiment of the present invention functions properly on a single equalizer.

Fig. 14 is a block diagram of the receiver in the fourth embodiment according to the present invention. An optical local oscillator 1 comprises a light source (laser diode) 92 and a driving circuit 94 which drives the light source 92 by controlling the oscillation frequency through the control of the bias current supplied to the light source 92. The optical local oscillator 1 comprises further an optical hybrid circuit 10 and an electrical 90° hybrid circuit 24, which are similar to those of the first to third embodiments, respectively. The output signal of a photodetector 12 is added with the output signal of an oscillator by a mixer 98 for up-conversion and the added signal is applied to an electrical 90° hybrid circuit 24. The output signal of a photodetector 14 is added with the output signal of the oscillator 96 by a mixer 100 for up-conversion and the added signal is applied to the electrical 90° hybrid circuit 24. An output signal of the electrical 90° hybrid circuit 24 at a first electrical output port 20 is applied through an equalizer 26 to a demodulator 30. An output signal of the electrical 90° hybrid circuit 24 at a second electrical output port 24 is applied to a frequency discriminator 102. The oscillation frequency of the local oscillator 1 is controlled in a feedback control mode so that the frequency of the input signal to the frequency discriminator 102 is constant.

The output photocurrents I_1 and I_2 of the photodetectors 12 and 14 are expressed by expressions (3) and (4).

The two electrical signals obtained by optical detection are added by mixers 98 and 100 with the output current I of the oscillator 96 having an angular frequency ω_{IF} ($\gg \omega_{OFF}$).

$I = C_3 \cos \omega_{IF} t$ (17)

where C_3 is an optional constant. The output currents i_1 and i_2 of the mixers 98 and 100 are expressed by the following expressions, in which $\mathrm{sgn}(\omega_S - \omega_L)$ is neglected for simplicity.

$i_1 = C_4 \cos (\omega_{OFF} t + \phi) \cos \omega_{IF} t = C_4 \cos A \cdot \cos B = (C_4/2)\{\cos (A + B) + \cos (B - A)\}$ (18)

$i_2 = -C_4 \sin (\omega_{OFF} t + \phi) \cos \omega_{IF} t = -C_4 \sin \nabla \cdot \cos B = (-C_4/2)\{\sin (A + B) - \sin (B - A)\}$ (19)

where C_4 is an optional constant and

$A = \omega_{OFF}t + \phi$ (20)
$B = \omega_{IF}t$ (21)

Conversion for delaying phase by 90° is represented by "*" and
$\cos(A + B) = \alpha$ (22)
$\cos(B - A) = \beta$ (23)
Then,
$\alpha^* = \sin(A + B)$
$\beta^* = \cos(B - A)$
Therefore expressions (18) and (19) can be rewritten as
$i_1 = (C_4/2)(\alpha + \beta)$ (24)
$i_2 = (-C_4/2)(\alpha^* - \beta^*)$ (25)

Accordingly, when the frequency-up-converted currents i_1 and i_2 are supplied to the electrical 90° hybrid circuit 24, the outputs of the electrical 90° hybrid circuit 24 are
$j_1 = i_1/2 + i_2^*/2 = (C_4/4)(\alpha + \beta) - (C_4/4)(\alpha^* - \beta^*)^* = (C_4/2)\alpha = (C_4/2)\cos\{(\omega_{IF} + \omega_{OFF})t + \phi\}$ (26)
$j_2 = i_1^*/2 + i_2/2 = (C_4/4)(\alpha + \beta)^* - (C_4/4)(\alpha^* - \beta^*) = (C_4/2)\beta^* = (C_4/2)\sin\{(\omega_{IF} - \omega_{OFF})t + \phi\}$ (27)

It is obvious from expression (26) that a photocurrent equal to that obtained through heterodyne detection using the IF ($\omega_{OFF} + \omega_{IF}$) is obtained. Accordingly, similarly to the procedure in the ordinary heterodyne system, the demodulator 30 is able to provide a baseband signal after applying the output current j_1 to the equalizer 26 to compensate dispersion in the optical fiber. Thus, the receiver in the fourth embodiment is effective for the enhancement of transmission speed and realizes a phase diversity system not requiring a light source with a very narrow spectral line width. Furthermore, the receiver is capable of compensating dispersion in the optical fiber. The output currents j_1 and j_2 may be used respectively for the AFC of the optical local oscillator 1 and the baseband signal demodulation.

The present invention is not limited to the foregoing specific embodiments in its practical application. For example, the optical hybrid circuit comprising, in combination, the components respectively for particular functions, such as optical couplers, may be substituted by a single device comprising a waveguide substrate carrying elements corresponding to all those components of the optical hybrid circuit to provide a compact receiver. Such a device provided with the light receiving elements of photodetectors directly formed on the waveguide substrate secures an accurate optical distance between the light receiving element and the optical coupler or the polarizing splitter to improve the reliability of the receiver.

Although the invention has been described in its preferred forms with a certain degree of particularity, obviously many changes and variations are possible therein. It is therefore to be understood that the present invention may be practiced otherwise than as specifically described herein without departing from the scope and spirit thereof.

Claims

1. A receiver for coherent optical communication comprising:
an optical local oscillator which emits a local-oscillator beam;
an optical hybrid circuit which is provided with a first optical input port for receiving a signal beam, a second optical input port for receiving the local-oscillator beam, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam, having a predetermined phase shift to the other pair respectively, and applies the added beams respectively to the first and second optical output ports;
a first photodetector for the photoelectric conversion of a beam received from the first optical output port of the optical hybrid circuit;
a second photodetector for the photoelectric conversion of a beam received from the second optical output port of the optical hybrid circuit;
an electrical 90° hybrid circuit which is provided with first and second electrical input ports for receiving the output signals of the first and second photodetectors, respectively, and first and second electrical output ports, adds the signal received at the first electrical input port to the signal received at the second electrical input port after shifting the phase of the former by 90° to obtain a added signal and applies the added signal to the second electrical output port, adds the signal received at the second electrical input port to the signal received at the first electrical input port after shifting the phase of the former by 90° to obtain a added signal and applies the added signal to the first electrical output port;
a first equalizer which delays a signal received from the first electrical output port by a delay corresponding

to the frequency of the same received signal;
a second equalizer which delays a signal received from the second electrical output port by a delay corresponding to the frequency of the same received signal;
a first demodulator which demodulates the output signal of the first equalizer;
a second demodulator which demodulates the output signal of the second equalizer; and
an adder which adds the respective output signals of the first and second demodulators.
2. A receiver for coherent optical communication comprising:
an optical local oscillator which emits a local-oscillator beam;
an optical hybrid circuit which is provided with a first optical input port for receiving a signal beam, a second optical input port for receiving the local-oscillator beam, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined chase shift to the other pair respectively, and applies the added beams respectively to the first and second optical output ports;
a first photodetector for the photoelectric conversion of a beam received from the first optical output port;
a second photodetector for the photoelectric conversion of a beam received from the second optical output port;
a first branching circuit for branching the output signal of the first photodetector;
a second branching circuit for branching the output signal of the second photodetector;
a first electrical 90° hybrid circuit which is provided with a first electrical input port which receives one of the output branched signals of the first branching circuit, a second electrical input port which receives one of the output branched signals of the second branching circuit, a first electrical output port and a second electrical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90° to provide a added signal and applies the same added signal to the second electrical output port, adds the signal applied to the second electrical input port to the signal applied to the first electrical input port after shifting the phase of the former by 90° to provide a added signal and applies the same added signal to the first electrical output port;
an inverter for inverting the polarity of the other output branched signal of either the first branching circuits or the second branching circuit;
a second electrical 90° hybrid circuit which is provided with a first electrical input port for receiving one of the other output branched signals, not applied to the inverter for polarity inversion, a second electrical input port for receiving the other output branched signal inverted by the inverter, a first electrical output port and a second electrical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90° to obtain a added signal and applies the same added signal to the second electrical output port, adds the signal applied to the second electrical input port to the signal applied to the first electrical input port after shifting the phase of the former by 90° to obtain a added signal and applies the same added signal to the first electrical output port;
first and second equalizers which delay a signal received from the first electrical output port of the first electrical 90° hybrid circuit and a signal received from the second electrical output port of the second electrical 90° hybrid circuit by delays corresponding to their frequencies, respectively, or delay a signal received from the second electrical output port of the first electrical 90° hybrid circuit and a signal received from the first electrical output port of the second electrical 90° hybrid circuit by delays corresponding to their frequencies;
a first demodulator for demodulating the output signal of the first equalizer;
a second demodulator for demodulating the output signal of the second equalizer; and
an adder for adding the output signals of the first and second demodulators.
3. A receiver for coherent optical communication comprising:
an optical local oscillator which emits a local-oscillator beam;
an optical hybrid circuit which is provided with a first optical input port which receives a signal beam, a second optical input port which receives the local-oscillator beam, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam, having a predetermined phase shift to the other pair respectively, and applies the added beams respectively to the first and second optical output ports;
a first photodetector for the photoelectric conversion of a beam received from the first optical output port of the optical hybrid circuit;
a second photodetector for the photoelectric conversion of a beam received from the second optical output port of the optical hybrid circuit;

an oscillator having a fixed frequency;
a first mixer which adds the output signal of the oscillator with the signal received from the first photodetector;
a second mixer which adds the output signal of the oscillator with the signal received from the second photodetector;
an electrical 90° hybrid circuit which is provided with a first electrical input port which receives the output signal of the first mixer, a second electrical input port which receives the output signal of the second mixer, a first electrical output port and a second elec trical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90° to provide a added signal and applies the same added signal to the second electrical output port, adds the signal applied to the second electrical input port to the signal applied to the first electrical input port after shifting the phase of the former by 90° to provide a added signal and applies the same added signal to the first electrical output port; and
an equalizer which delays the output signal received from the first or second electrical output port by a delay corresponding to its frequency.
4. A receiver for coherent optical communication comprising:
a first optical branching circuit for branching a received signal beam;
an optical local oscillator which emits a local-oscillator beam;
a second optical branching circuit for branching the local-oscillator beam;
a first optical hybrid circuit which is provided with a first optical input port which receives one of the branched beams of the signal beam branched by the first optical branching circuit, a second optical input port which receives one of the branched beams of the local-oscillator beam branched by the second optical branching circuit, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams to the first and second optical output ports, respectively;
a second optical hybrid circuit which is provided with a first optical input port which receives the other branched beam of the signal beam branched by the first optical branching circuit, a second optical input port which receives the other branched beam of the local-oscillator beam branched by the second optical branching circuit, a first optical output port and a second optical output port, branches the signal beam and the local-oscillator beam, adds one pair of the branched beams pairs of each of the signal beam and the local-oscillator beam having a predetermined phase shift to the other pair respectively, and applies the added beams to the first and second optical output ports, respectively;
first to fourth photodetectors respectively for the photoelectric conversion of the output beams received from the first and second optical output ports of the first optical hybrid circuit and the first and second output ports of the second optical hybrid circuit;
a first electrical 90° hybrid circuit which is provided with a first electrical input port which receives the output signal of the first photodetector, a second electrical input port which receives the output signal of the second photodetector, a first electrical output port and a second electrical output port, adds the input signal applied to the first electrical input port to the input signal applied to the second electrical input port after shifting the phase of the former by 90° to obtain a added signal, applies the same added signal to the second electrical output port, adds the input signal applied to the second electrical input port to the input signal applied to the first input port after shifting the phase of the forner by 90° to obtain a added signal and applies the same added signal to the first electrical output port;
a second electrical 90° hybrid circuit which is provided with a first electrical input port which receives the output signal of che third photodetector, a second electrical input port which receives the output signal of the fourth photodetector, a first electrical output port and a second electrical output port, adds the signal applied to the first electrical input port to the signal applied to the second electrical input port after shifting the phase of the former by 90° to obtain a added signal, applies the same added signal to the second electrical output port, adds the signal applied to the second electrical input port to the signal applied to the first electrical input port after shifting the phase of the former by 90° to provide a added signal and applies the same added signal to the first electrical output port;
first and second equalizers which delay the output signals received from the first electrical output port of the first electrical 90° hybrid circuit and the second electrical output port of the second electrical 90° hybrid circuit by delays respectively corresponding to their frequencies, or delay the output signals received from the second electrical output port of the first electrical 90° hybrid circuit and the output signal received from the first electrical output port of the second electrical 90° hybrid circuit by delays respectively corresponding to their frequencies;

first and second demodulators respectively for demodulating the output signals of the first and second equalizers; and
an adder for adding the output signals of the first and second demodulators.
5. A receiver for coherent optical communication according to Claim 1, wherein the sign of the proportional constant of either the first equalizer or the second equalizer, for determining the delay according to the frequency is positive and the sign of the proportional constant of the other, for determining the delay according to the frequency is negative.
6. A receiver for coherent optical communication according to Claim 2 or 4, wherein the respective signs of the proportional constants of the first and second equalizers, for determining the delay according to the frequency are the same.
7. A receiver for coherent optical communication according to Claim 5 or 6, herein the optical hybrid circuit comprises: an optical coupler which adds the signal beam applied to the first optical input port to the local-oscillator beam applied to the second optical input port and branches the added beam to provide branched beams; and a polarizing splitter which splits at least one of the branched beams branched by the optical coupler so that the polarized components of the signal beam and the local-oscillator beam are applied to the first and second optical output ports.
8. A receiver for coherent optical communication according to Claim 7, wherein either the input signal beam or the input local oscillator beam to the optical hybrid circuit is a linearly polarized beam and the other is a circularly polarized beam.
9. A receiver for coherent optical communication according to Claim 7, wherein the input signal beam and the input local-oscillator beam are elliptically polarized beams having the same phase shift corresponding to the phase difference between the linearly polarized beam and the circularly polarized beam.
10. A receiver for coherent optical communication according to Claim 5 or 3, wherein the optical hybrid circuit comprises: first and second polarizing splitters for splitting the signal beam applied to the first optical input port and the local-oscillator beam applied to the second optical input port so that the polarized components of the signal beam and the local-oscillator beam are provided; and first and second optical couplers which add the output beams having the same plane of polarization provided by the first and second polarizing splitters and apply the added beams to the first and second optical output ports.
11. A receiver for coherent optical communication according to Claim 3, wherein the optical hybrid circuit comprises: an optical coupler which adds the signal beam applied to the first optical input port to the local-oscillator beam applied to the second optical input port and branches the added beam; and a polarizing splitter splits at least one of the branched beams branched by the optical coupler so that the respective polarized components of the signal beam and the local-oscillator beam are applied to the first and second optical output ports.
12. A receiver for coherent optical communication according to Claim 7 or 11, wherein either the signal beam or the local-oscillator beam applied to the optical hybrid circuit is a linearly polarized beam and the other is a circularly polarized beam.
13. A receiver for coherent optical communication according to Claim 7 or 11, wherein the signal beam and the local-oscillator beam applied to the optical hybrid circuit are elliptically polarized beams having the same phase shift corresponding to the phase difference between the linearly polarized beam and the circularly polarized beam.
14. A receiver for coherent optical communication according to Claim 6, wherein the optical hybrid circuit comprises: first and second polarizing splitters which splits the signal beam and the local-oscillator beam applied respectively to the first and second optical input ports so that the polarized components of the signal beam and the local-oscillator beam are provided; and first and second optical couplers which add the output beams having the same plane of polarization provided by the first and second polarizing splitters and apply the added beams to the first and second optical ports.
15. A receiver for coherent optical communication according to Claim 10 or 14, wherein either the signal beam or the local-oscillator beam applied to the optical hybrid circuit is a linearly polarized beam and the other is a circularly polarized beam.
16. A receiver for coherent optical communication according to Claim 10 or 14, wherein the signal beam and the local-oscillator beam applied to the optical hybrid circuit are elliptically polarized beams having the same phase shift corresponding to the phase difference between the linearly polarized beam and the circularly polarized beam.
17. A receiver for coherent optical communication according to Claim 10, wherein the signal beam and the local-oscillator beam are elliptically polarized beams having the same phase shift corresponding to the phase difference between the linearly polarized beam and the circularly polarized beam.
18. A receiver for coherent optical communication according to Claim 6, wherein each of the first and

second optical hybrid circuits comprises: an optical coupler which adds the signal beam applied to the first optical input port to the local-oscillator beam applied to the second optical input port and branches the added beam to provide branched beams; and a polarizing splitter which splits at least one of the branched beams branched by the optical coupler so that the polarized components of the signal beam and the local-oscillator beam are applied to the first and second optical output ports.

19. A receiver for coherent optical communication according to Claim 18, wherein either the signal beam or the local-oscillator beam applied to the first and second optical hybrid circuits is a linearly polarized beam and the other is a circularly polarized beam.

20. A receiver for coherent optical communication according to Claim 19, wherein the respective planes of polarization of the linearly polarized beams applied respectively to the first and second optical hybrid circuits are orthogonal, and the respective directions of rotation of the circularly polarized beams applied respectively to the first and second optical hybrid circuits are the same.

21. A receiver for coherent optical communication according to Claim 19, wherein the respective planes of polarization of the linearly polarized beams applied respectively to the first and second optical hybrid circuits are parallel, and the respective directions of rotation of the circularly polarized beams applied respectively to the first and second optical hybrid circuits are opposite to each other.

22. A receiver for coherent optical communication according to Claim 18, wherein the signal beam and the local-oscillator beam applied to the first and second optical hybrid circuits are elliptically polarized beams having the same phase shift corresponding to the phase difference between the linearly polarized beam and the circularly polarized beam.

23. A receiver for coherent optical communication according to Claim 6, wherein each of the first and second optical hybrid circuits comprises: first and second polarizing splitters for splitting the signal beam applied to the first optical input port and the local-oscillator beam applied to the second optical input port so that the polarized components of the signal beam and the local-oscillator beam are provided; and first and second optical couplers which add the output beams having the same plane of polarization provided by the first and second polarizing splitters and apply the added beams to the first and second optical output ports.

24. A receiver for coherent optical communication according to Claim 23, wherein either the signal beam or the local-oscillator beam applied to the first and second optical hybrid circuits is a linearly polarized beam and the other is a circularly polarized beam.

25. A receiver for coherent optical communication according to Claim 24, wherein the respective planes of polarization of the linearly polarized beams applied to the first and second optical hybrid circuits are orthogonal, and the respective directions of rotation of the circularly polarized beams applied to the first and second optical hybrid circuits are the same.

26. A receiver for coherent optical communication according to Claim 24, wherein the respective planes of polarization of the linearly polarized beams applied to the first and second optical hybrid circuits are parallel, and the respective directions of rotation of the circularly polarized beams applied to the first and second optical hybrid circuits are opposite to each other.

27. A receiver for coherent optical communicaticn according to Claim 23, wherein the signal beam and the local-oscillator beam applied to the first and second optical hybrid circuits are elliptically polarized beams having the same phase shift corresponding to the phase difference between the linearly polarized beam and the circularly polarized beam.

FIG. 1

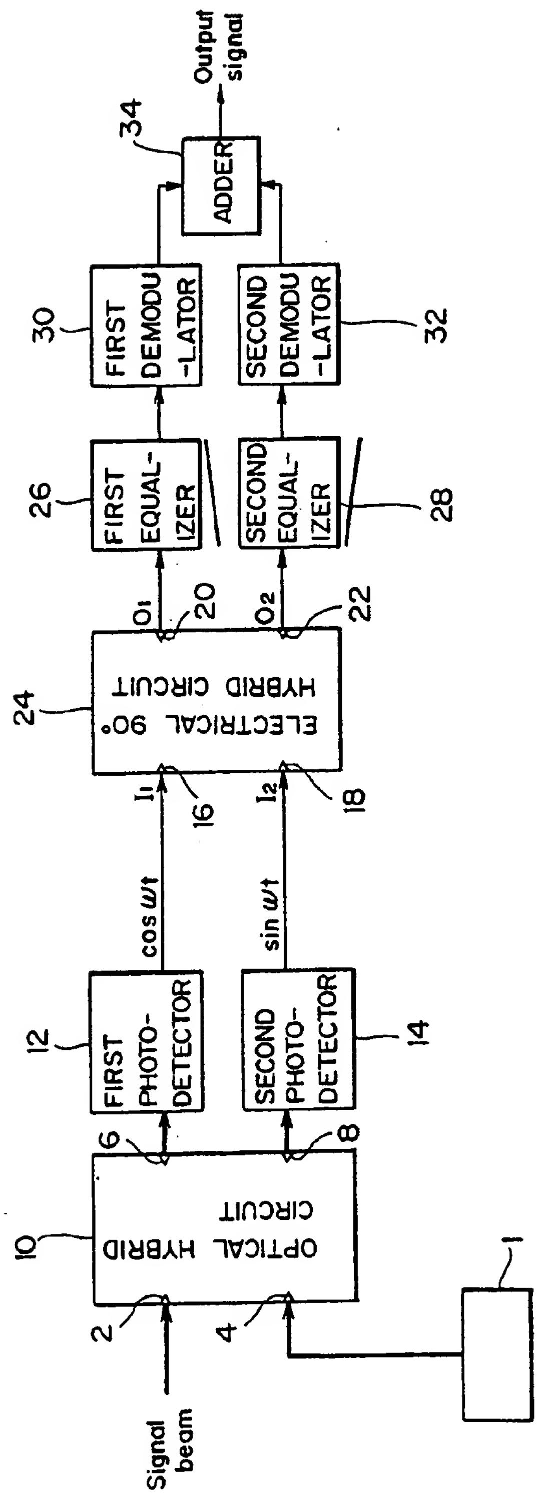

Signal beam
OPTICAL HYBRID CIRCUIT
FIRST PHOTO-DETECTOR
SECOND PHOTO-DETECTOR
cos ωt
sin ωt
I1
I2
ELECTRICAL 90° HYBRID CIRCUIT
O1
O2
FIRST EQUAL-IZER
SECOND EQUAL-IZER
FIRST DEMODU-LATOR
SECOND DEMODU-LATOR
ADDER
Output signal
1
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34

FIG. 2

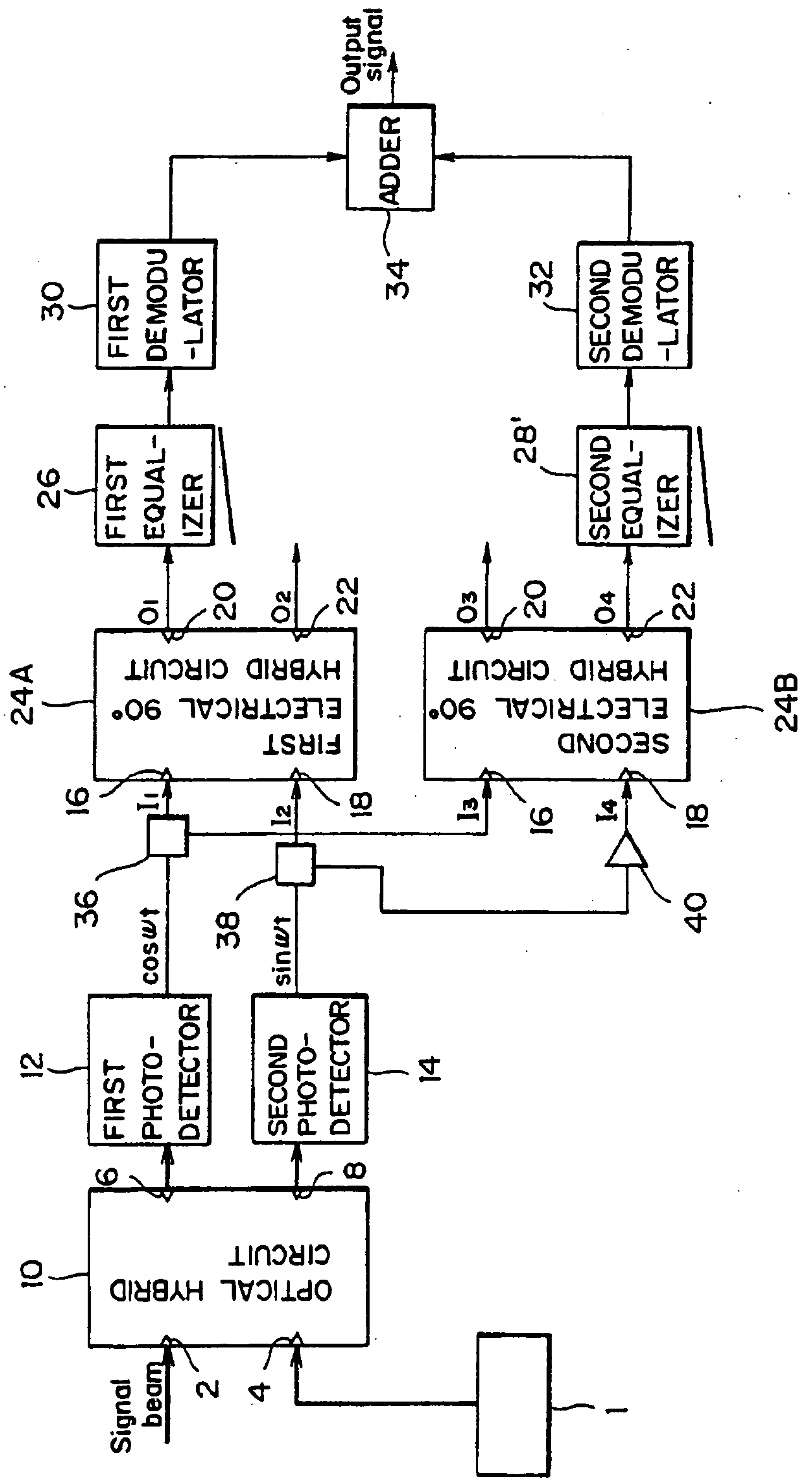

Signal beam
OPTICAL HYBRID CIRCUIT
FIRST PHOTO-DETECTOR
SECOND PHOTO-DETECTOR
cosωt
sinωt
FIRST ELECTRICAL 90° HYBRID CIRCUIT
SECOND ELECTRICAL 90° HYBRID CIRCUIT
FIRST EQUAL-IZER
SECOND EQUAL-IZER
FIRST DEMODU-LATOR
SECOND DEMODU-LATOR
ADDER
Output signal
24A
24B
28'

FIG. 3

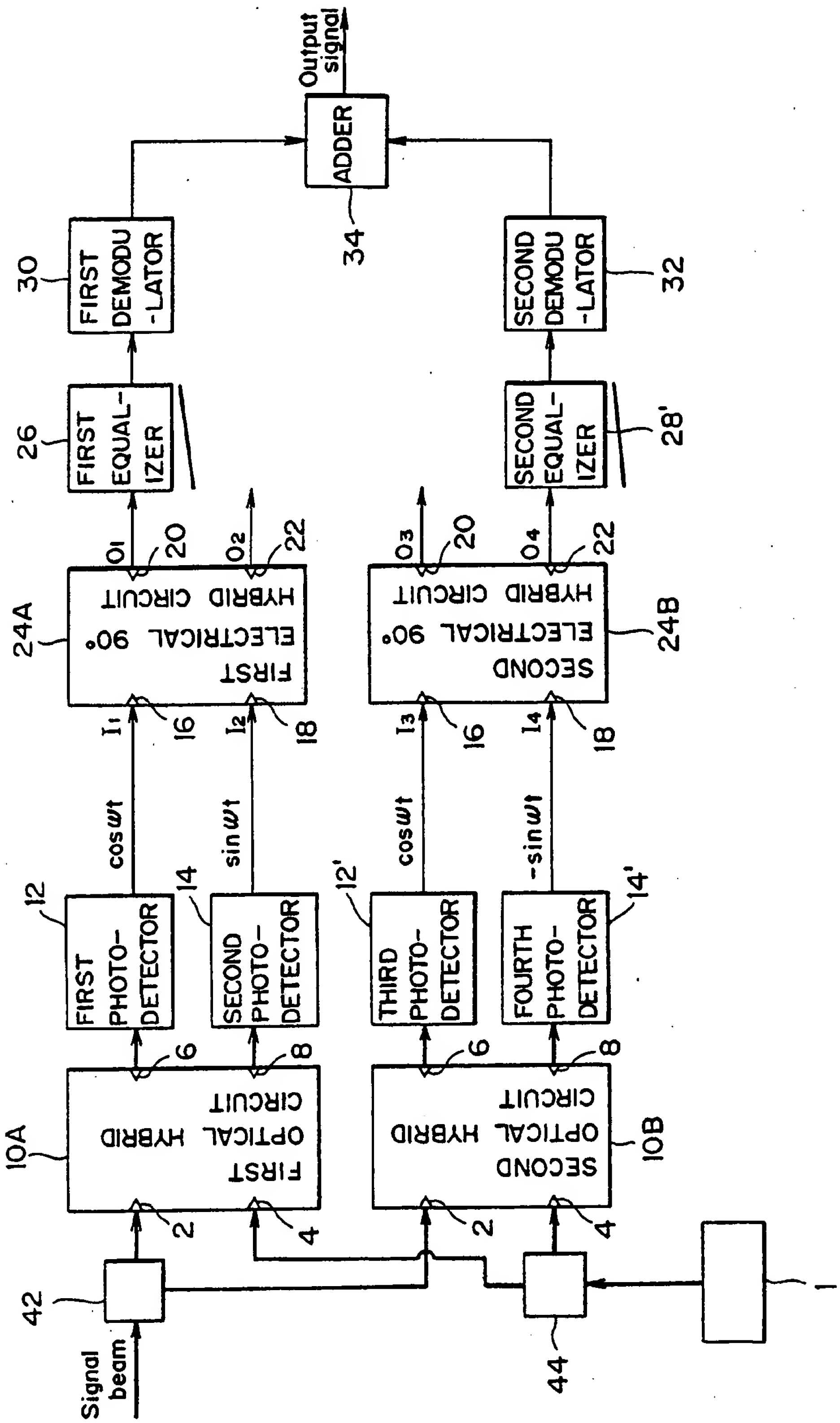

Signal beam
FIRST OPTICAL HYBRID CIRCUIT
SECOND OPTICAL HYBRID CIRCUIT
FIRST PHOTO-DETECTOR
SECOND PHOTO-DETECTOR
THIRD PHOTO-DETECTOR
FOURTH PHOTO-DETECTOR
cosωt
sinωt
cosωt
-sinωt
FIRST ELECTRICAL 90° HYBRID CIRCUIT
SECOND ELECTRICAL 90° HYBRID CIRCUIT
FIRST EQUAL-IZER
SECOND EQUAL-IZER
FIRST DEMODU-LATOR
SECOND DEMODU-LATOR
ADDER
Output signal

FIG. 4A

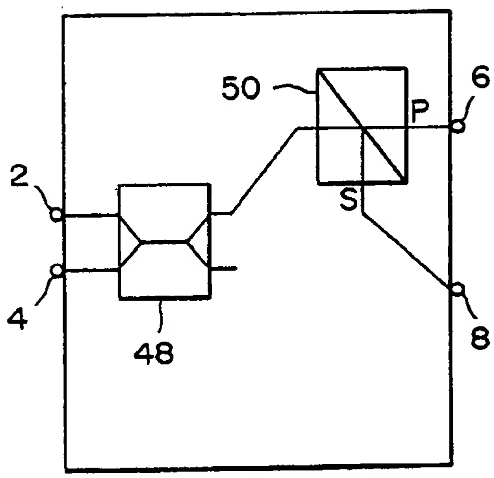


FIG. 4B

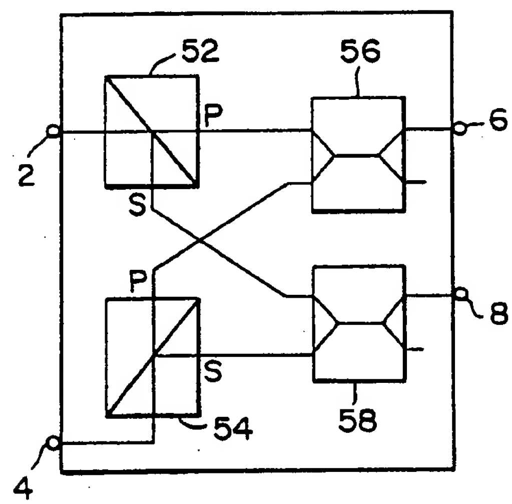


FIG. 4C

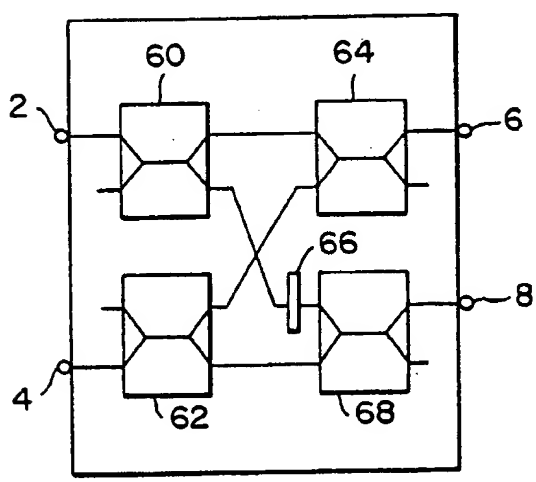


FIG. 5

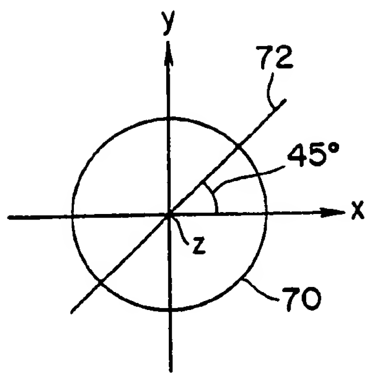


FIG. 6A

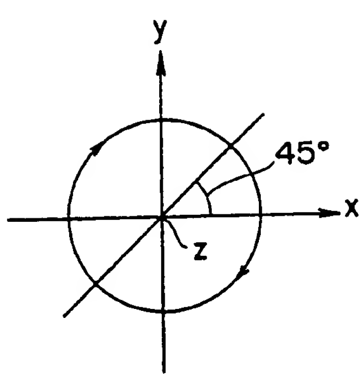


FIG. 6B

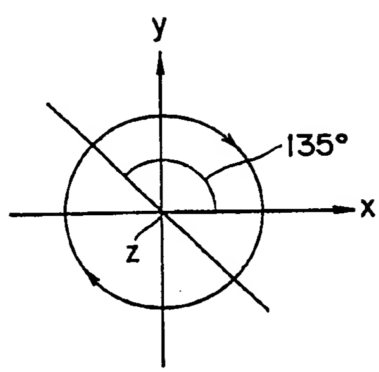


FIG. 7A

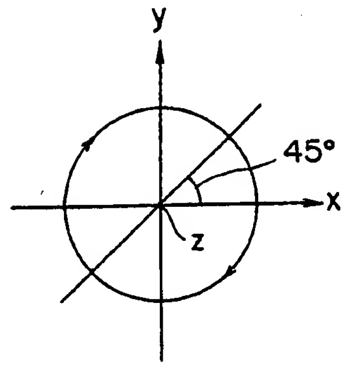


FIG. 7B

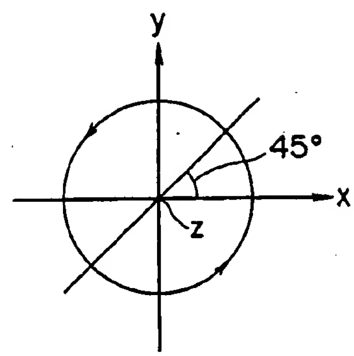


FIG. 8

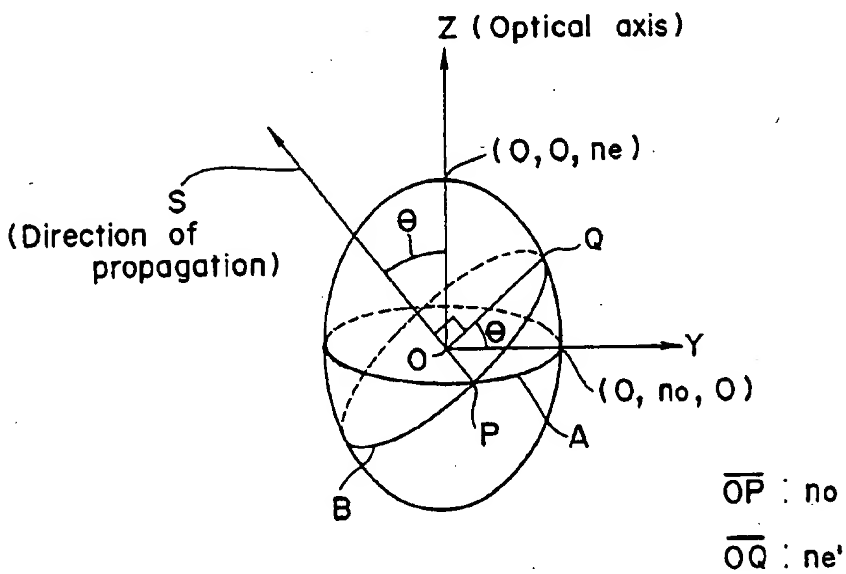


FIG. 9A

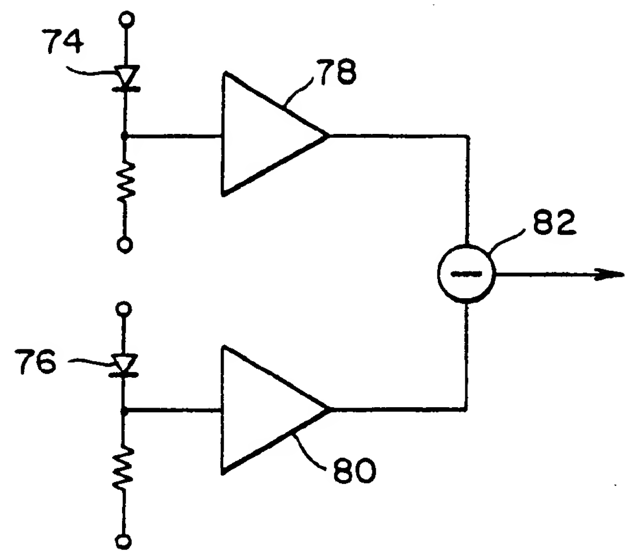


FIG. 9B

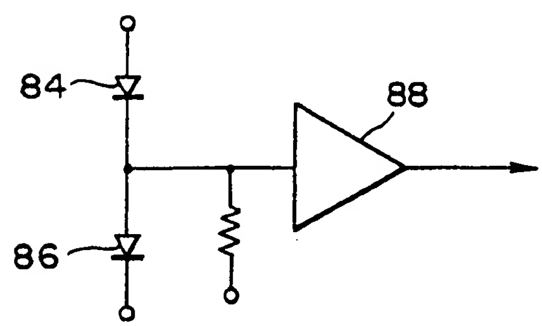


FIG. 10A

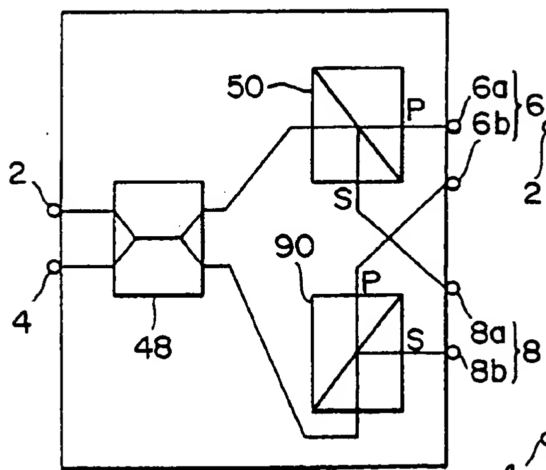


FIG. 10B

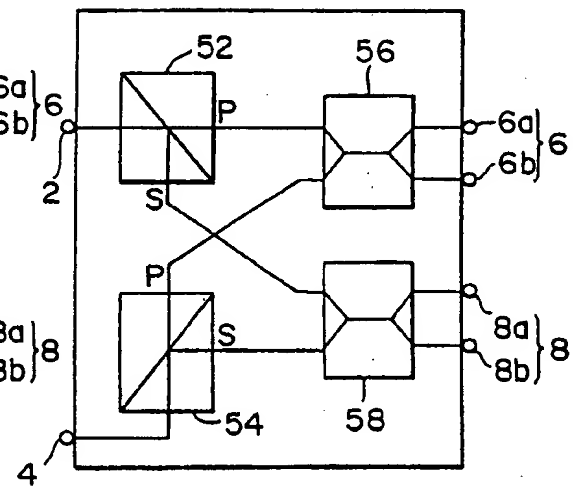


FIG. 10C

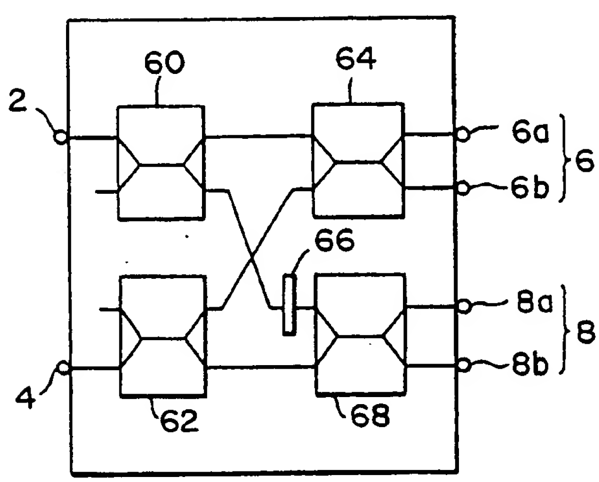
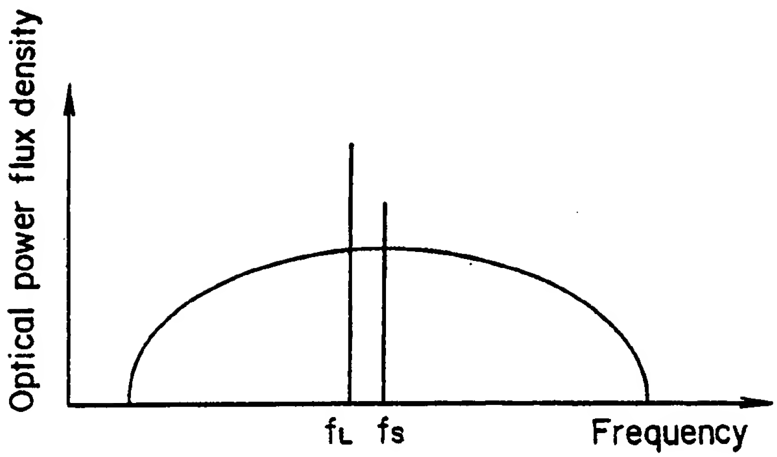
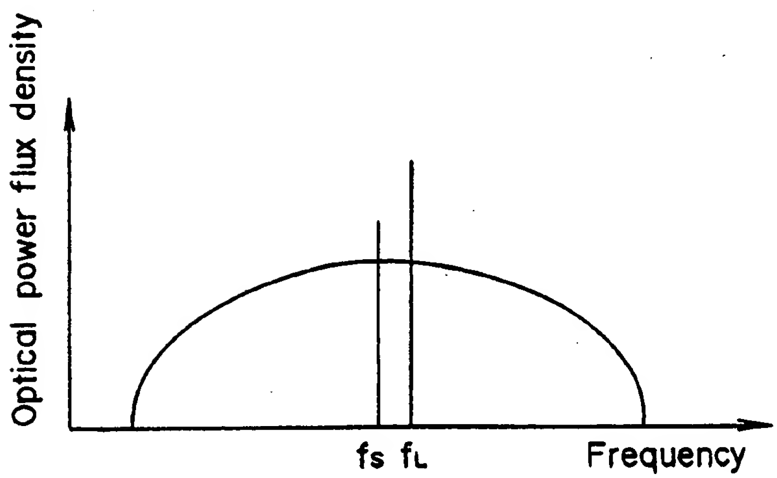


FIG. 11A



$f_L < f_s$

FIG. 11B



$f_s < f_L$

FIG. 12A

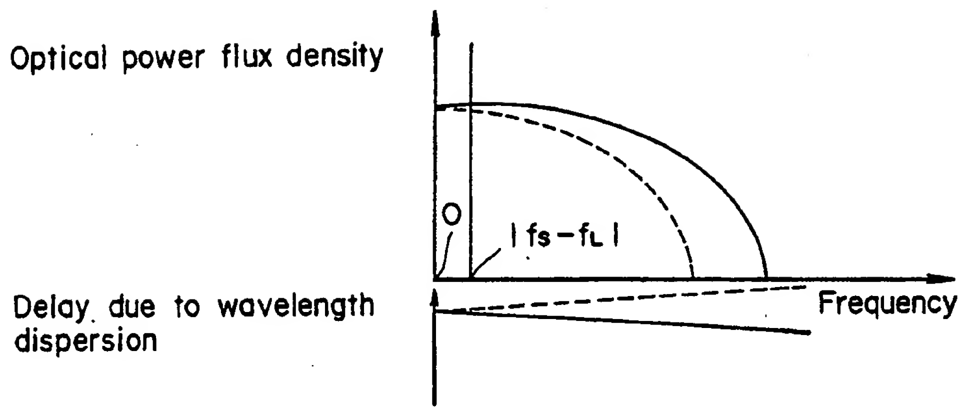


FIG. 12B

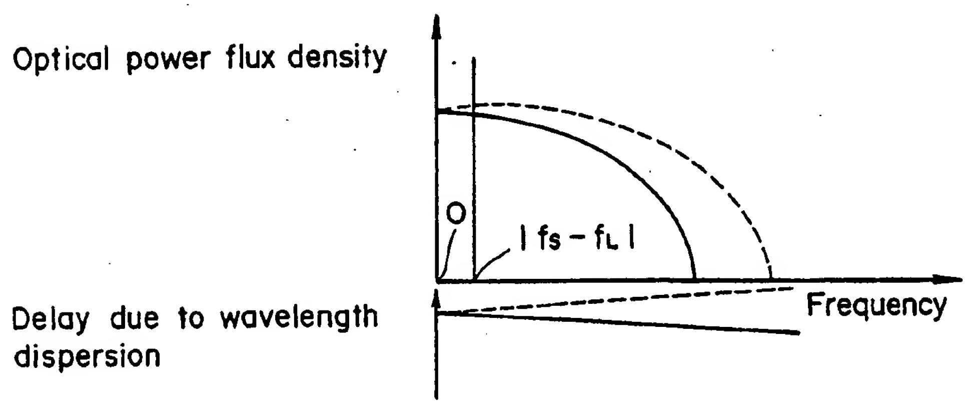


FIG. 13A

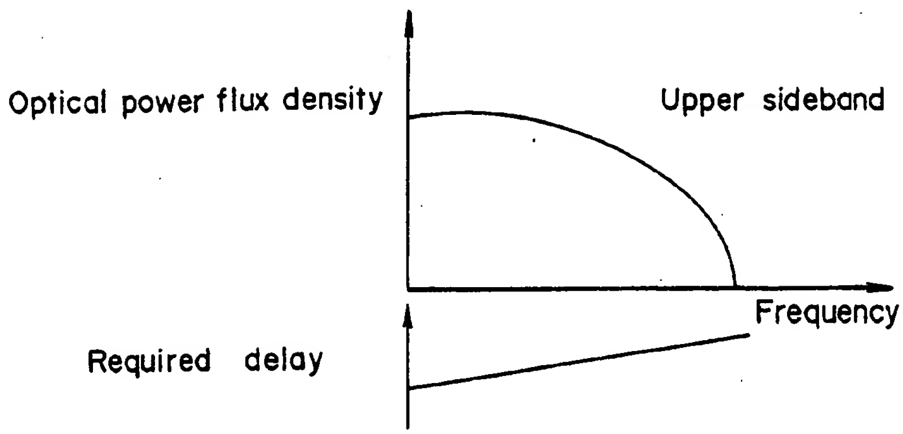


FIG. 13B

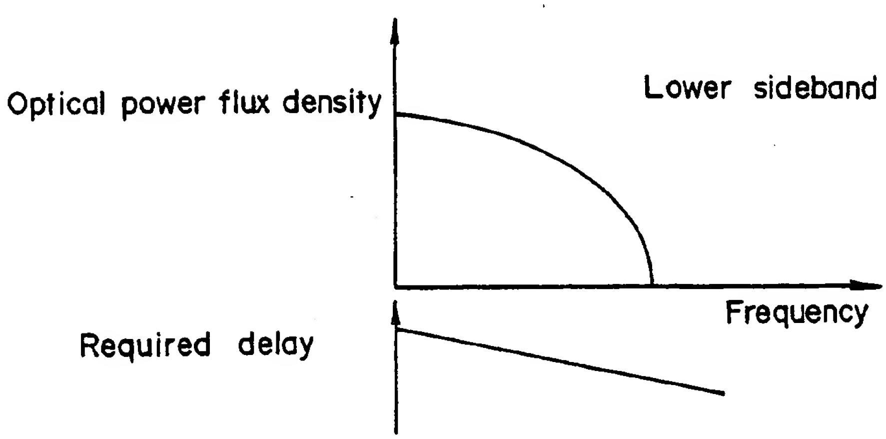
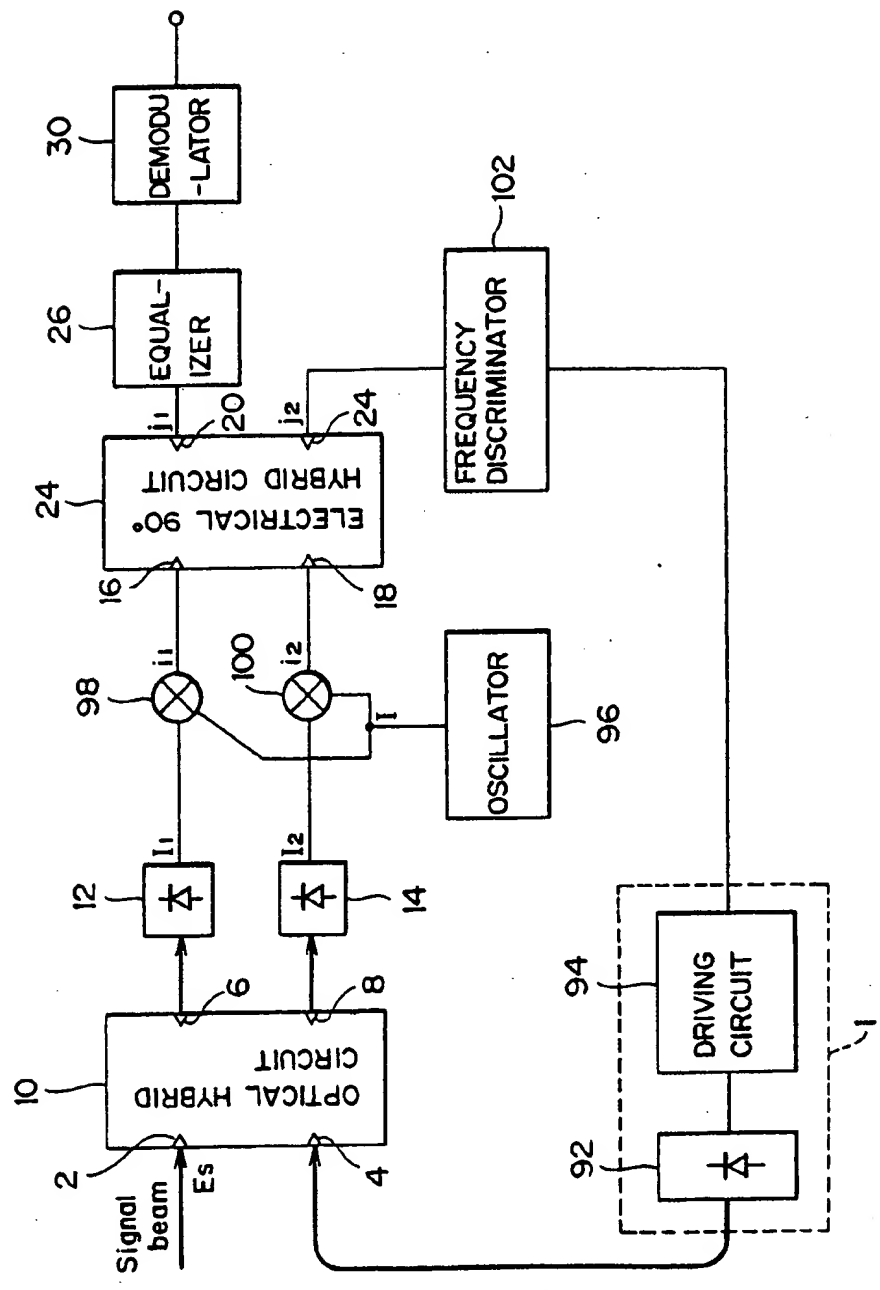


FIG. 14


Signal beam
Es
2
4
10
OPTICAL HYBRID CIRCUIT
6
8
12
14
I1
I2
98
100
i1
i2
I
OSCILLATOR
96
16
18
24
ELECTRICAL 90° HYBRID CIRCUIT
20
24
j1
j2
26
EQUAL-IZER
30
DEMODU-LATOR
FREQUENCY DISCRIMINATOR
102
92
94
DRIVING CIRCUIT
1